B

◄CONTENTS Orthopedic Technology Review VOL 2 NO 2 FEBRUARY 2000

Advances in Orthopedics

The Evolution of Joint Implants

By Joseph F. Fetto, MD

Part I: Throughout the 20th century, advances in orthopedic implants paralleled the technological developments of the times.

In 2001, more than a half million individuals around the world may have undergone surgical replacement of a painful, arthritic hip joint. As we enter the 21st century, it is fitting to stop, look back, and gain perspective on where hip replacement arthroplasty began, how it arrived where it is today, and the directions in which joint implants are heading.

Like aviation and many of the other technological developments of the 20th century, joint replacement with orthopedic implants has evolved far beyond its origins as a seat-of-the-pants endeavor. Many of the advances that we take for granted today came about through the courageous efforts of the early barnstormers/surgeons. Those early pioneers (including Jones, Smith-Petersen, Moore, Aufranc, Thompson, Judet, Muller, and Charnley) deserve great credit for their innovations. For example, if an articulation is a perfect nonunion where painless movement can occur between the ends of two bones, Sir Robert Jones made excellent sense in 1913 when he proposed the creation of a mobile, painless arthroplasty by inserting a piece of gold foil between the damaged femoral head and acetabulum of an arthritic hip. His attempt at the first interpositional arthroplasty, although crude, was an example of the creativity that historically has characterized the work of implant surgeons.

Trial-and-Error Methods

As was the case for the early aeronautical engineers, orthopedic surgeons and researchers could advance only as quickly as the tools that they required became available. They were forced to employ an empirical methodology when studying the problems that confronted them. Typically, a surgeon, having seen a recurring problem among his patients, would propose a solution: replace a worn/deformed femoral head with a glass ball; use acrylic cement to achieve better fixation of an implant to the host bone; or use Teflon as an inert, frictionless bearing surface with which to replace a worn articular surface. Then the idea would be tested in a series of patients, with the results tabulated and analyzed in the hope that a successful outcome would be achieved in the majority of cases.

Studies were performed both prospectively and retrospectively. They produced much important and useful information. However, in spite of the best efforts of the surgeons/researchers to help patients and avoid doing harm, studies sometimes, to the chagrin of the surgeons/researchers and the detriment of the patients, exposed (too late) an unrecognized or unanticipated fundamental flaw in the original concept.

Early implants composed of wood, ivory, and metals were not biocompatible or sufficiently strong. Glass and ceramics fractured under physiologic loads. Frictionless materials did not always wear well under physiologic demands. Bioactive materials (osteoinductive ceramics) were sometimes found to be the source of third-body wear debris. In some metals, casting produced an unacceptably weak material with which to replace a hip. Implant-surface preparations were not always stable or permanent, resulting in an additional source of wear debris. Cement gave off a very significant amount of heat, a potential cause of thermal damage to adjacent tissues. Too late, it was

appreciated that cement needed to be made radiopaque for later imaging, that it needed to be stained so as to be easily differentiated from bone during revision surgeries, and that its monomer component had a significant effect on the cardiopulmonary system.

Clinical Observation

Just as early aircraft designers tried to understand the subtleties of flight, orthopedic surgeons struggled to determine the principles of the hip's function. Through their powers of observation, like DaVinci studying the flight of birds, orthopedists attempted to overcome the shortcomings of the technology of their time. Their observations were limited, however, to cadavers and skeletons. They were unable to simulate and control the dynamic contribution and effect of muscle forces. Because early researchers were restricted in this way, it is not surprising that they sometimes created models and drew conclusions that were incomplete or inaccurate.

Another difficulty that the lack of technological sophistication posed for researchers working before the advent of computers concerned the way in which problems were approached. Early researchers found it impossible to isolate the effects of many simultaneously interacting variables. For this reason, factors were studied in a serial (rather than holistic) fashion. It is understandable, being handicapped in this way, that researchers sometimes failed to recognize a good idea — such as the potential benefit of hard/hard bearing surfaces over metal/plastic surfaces — because the entire construct was compromised due to the failure of some other unrelated factor. For example, femoral-neck–acetabular impingement in McKee-Ferrar components led to compromises in bone/implant fixation.

Much like the US National Aeronautics and Space Administration (NASA) for aviation, the modern field of orthopedics has come a long way from its early trial-and-disaster approach to progress. Today, as in the past, implant-related issues may be divided into four major categories: design, fixation, bearing surface, and materials. It is no longer necessary, however, to study these variables in isolation from one another. Orthopedists, like NASA, employ available technology, but they have found that it is no longer acceptable (nor is it necessary) to put people or dollars at risk before thoroughly modeling, studying, and understanding all aspects of a problem.

Computer modeling, simulations, and virtual-reality techniques now permit the practical and ethical study of multiple variables simultaneously, without exposing patients to risk. The degree to which progress in orthopedics has paralleled that in other disciplines can be exemplified by the evolution and development of biomechanical models of the hip joint.

Hip-Joint Models

During the 19th century, there were two competing opinions concerning how the hip was loaded during gait. Both accepted that the center of gravity of the body was in the midline, approximately 2 cm anterior to the second sacral vertebra. From this common starting point, however, the two camps reached diametrically different conclusions regarding the forces experienced by the femur during gait. Their views reflected their fundamentally different approaches to the problem. One school of thought, represented in the writings of Culman (an engineer), was very mechanical in its approach. Its proponents compared the function of the femur to that of a cantilevered crane. The second school of thought approached the problem from a histological viewpoint. It has been commonly accepted that the structure of a bone reflects its loading history. This concept has been so well accepted by the orthopedic community that it is usually referred to as Wolff's Law. In general, it states that compressive forces are associated with (and are a stimulus for) the formation of cortical bone, and that cancellous bone is associated with areas of tension load, such as apophyses.

The crane analogy was intuitively obvious. It made the simple conclusion that because, during the unilateral stance phase of gait, the body's center of gravity is medial to the entire supporting limb, the hip will experience a downward-directed compression force and an inward (varus) bending moment. The result of these loads would be the creation of a compression stress along the medial aspect of the femur and a tension stress along the lateral aspect of the femur (Figure 1). This model was consistent with clinical experience of the varus collapse of proximal femoral fractures.

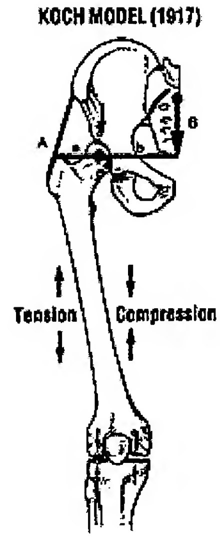

Figure 1. Koch model of the hip.

Members of the opposition demonstrated that metaphyseal trabeculae from the medial (compression) region and lateral (tension) region of the proximal femur were histologically indistinguishable. They also showed that, in every femur, there is dense cortical bone along the entire lateral aspect, from the apophyseal line of the greater trochanter to the epiphyseal line proximal to the knee. Their position was that if Wolff's Law were valid, these observations could be explained only by the existence of similar (but not necessarily equal) forces acting on the femur, and that these forces are most consistent with compressive loads. In this way, they attempted to explain the varus deformity seen in femur fractures as the consequence of the inequality of the medial and lateral compressive forces that the femur would experience during weight bearing. They concluded, therefore, that during the unilateral stance phase of gait, there must be compression loading along both the medial and lateral aspect of the femur. Only in this way would it be possible to explain the presence of cortical bone in the lateral femur (Figure 2) and the similarity of trabecular structures in the proximal femur.


Figure 2. Cortical bone in the lateral femur.

Neither side was able to prove its argument definitively. In 1917, Koch1 of Johns Hopkins University, Baltimore, published a lengthy dissertation on the subject in the American Journal of Anatomy. Koch presented his mathematical analysis of the forces present in a cadaveric femur during the unilateral support phase of gait. His classic article described the quantity of medial compression and lateral tension loads experienced along the length of the femur, and he went on to explain how the gluteus medius muscle acted to counterbalance the inward varus moment created by the body's center of gravity. He described how the lever arms of the body and the abductor muscle were seen in the ratio of 2:1. This led him to state that the abductor muscle must generate twice the force of the body's weight in order to maintain equilibrium and prevent the body from falling toward the unsupported side.

Koch's treatise was so powerfully presented that it stood unchallenged as the definitive model of hip biomechanics for the next 70 years. It was the foundation for the design, testing, and validation of hip-replacement prostheses. All was not well with Koch's model of reality, however. Although it seemed to provide a reasonable explanation of fracture mechanics, it was plagued by nagging internal inconsistencies beyond those raised by the histological model of the previous century. Until the advent of powerful computer technologies, these inconsistencies would remain unexplained.

The second part of this two-part article will appear in the March issue of Orthopedic Technology Review.

Joseph F. Fetto, MD, is associate professor of Orhopedics at New York University Medical Center, New York City. His principal area of research interest involves biomechanical issues of design and materials as they relate to joint arthroplasty.

Reference

1. Koch J. The laws of bone architecture. *American Journal of Anatomy.* 1917;21:177-201.